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Initial-state quark energy loss from Drell–Yan production in proton-proton and proton-nucleus collisions

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Abstract

Drell–Yan production cross sections were measured by the NA3 and E866 experiments, in p-Pt and pp collisions, as a function of the dimuon mass and x_F. We compare these measurements to next-to-leading order Drell–Yan calculations, made with the CTEQ6M parton densities modified (or not) by nuclear effects, using the EPS09 parameterization. The analysis of the data allows us to evaluate the initial-state quark energy loss. Drell–Yan measurements are ideally suited to isolate the initial-state parton energy loss, given the absence of final-state effects on the produced dimuon. Our study shows that these data indicate negligible quark energy loss and allow us to derive rather strict upper limits. For completeness, our study has been repeated using the less accurate measurements of Drell–Yan cross section ratios between heavy and light nuclear targets, provided by the E772 and E866 experiments. Our results provide an additional constraint on the models trying to explain quarkonium production in proton-nucleus collisions, as a function of quarkonium rapidity and collision energy, where initial- and final-state energy loss has frequently been assumed to play an important role, convoluted with several other complex mechanisms, including final-state quarkonium break-up, formation time effects, etc.

Keywords: Quark energy loss, Drell–Yan, nuclear effects in quarkonium production

Quarkonium production in proton-nucleus collisions is affected by a multitude of cold nuclear matter effects and it is essentially impossible to disentangle them if we only look at a single kind of measurements, like the nuclear dependence of the J/ψ production cross section. Since the produced lepton pair does not interact with the nuclear medium, Drell–Yan production is not affected by final-state effects and should exclusively reflect nuclear effects on the parton distribution functions and energy loss by the quarks (and gluons) before the partonic interaction. Studies of Drell–Yan data may, hence, provide pertinent constraints when interpreting quarkonium production results in terms of initial-state nuclear effects.

Before interpreting discrepancies between next-to-leading order (NLO) Drell–Yan calculations [1] and the proton-nucleus data as a sign of nuclear effects, we need to ensure that the calculations provide a very good description of pp data, where no such effects exist. We made this validation using the double-differential Drell–Yan cross section measurement of the E866 experiment [2], at $E_{\mathrm{lab}} = 800$ GeV, available in 16×9 dimuon cells, in x_F from 0 to 0.8 and in mass from 4.2 to 8.7 GeV/c^2. The agreement is truly remarkable, as illustrated in Figs. 1 and 2, after scaling the calculations by a global factor, $K = 1.124 \pm 0.007$ (not much larger than unity, considering that the measurement has an overall normalization uncertainty of ±6.5 %). This gives us confidence that the calculations give a very good description of Drell–Yan production in the absence of nuclear effects.

Our evaluation of the initial-state parton energy loss is based on the simple idea that the beam parton loses a (constant) fraction, $\epsilon_{q,g}$, of its energy each time it encounters a nucleon in the target nucleus, until it undergoes the hard scattering where the Drell–Yan dimuon is created. More precisely, if the beam parton is a quark and has momentum fraction x_1, the parton density function is evaluated for that x_1 value while the partonic cross section is calculated using $x_1' = x_1 \cdot (1 - \epsilon_q)^{N-1}$,

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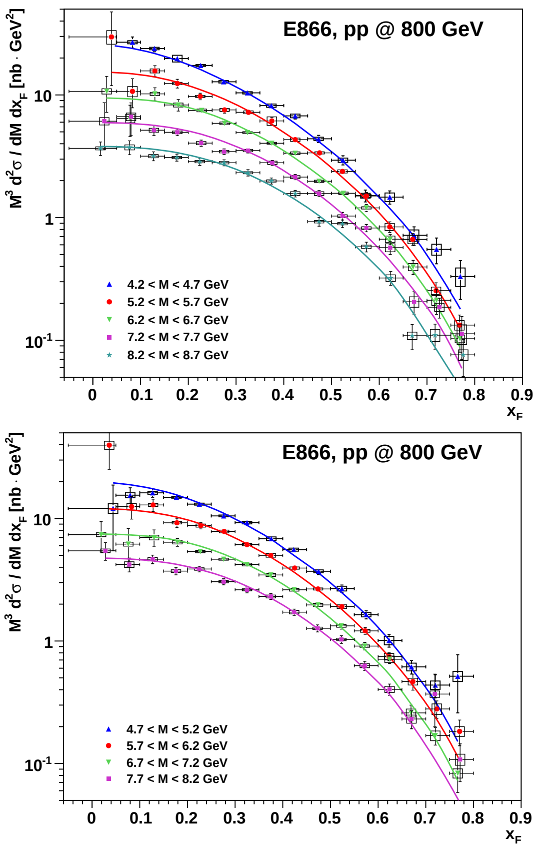

Figure 1: Drell–Yan production cross section vs. dimuon x_{F} and mass, as measured by the E866 experiment and as calculated at NLO.

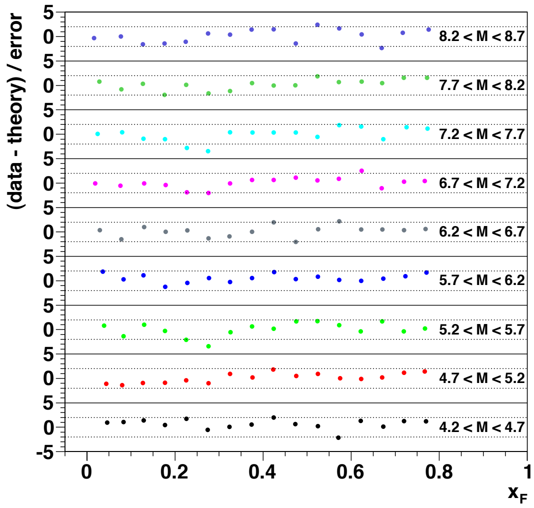

Figure 2: Almost all of the 16×9 E866 measurements are within $2\,\sigma$ of the theoretical calculation (denoted by the dashed lines).

where N is the number of soft scatterings that the quark suffers in the nuclear target (calculated with the Glauber formalism). Gluons also contribute to Drell–Yan production (at NLO, $qg \to q\gamma^*$) and the corresponding parameter, ϵ_{g}, is bound to the quark value by the ratio of the Casimir factors, $\epsilon_{\mathrm{g}} = 9/4 \cdot \epsilon_{\mathrm{q}}$.

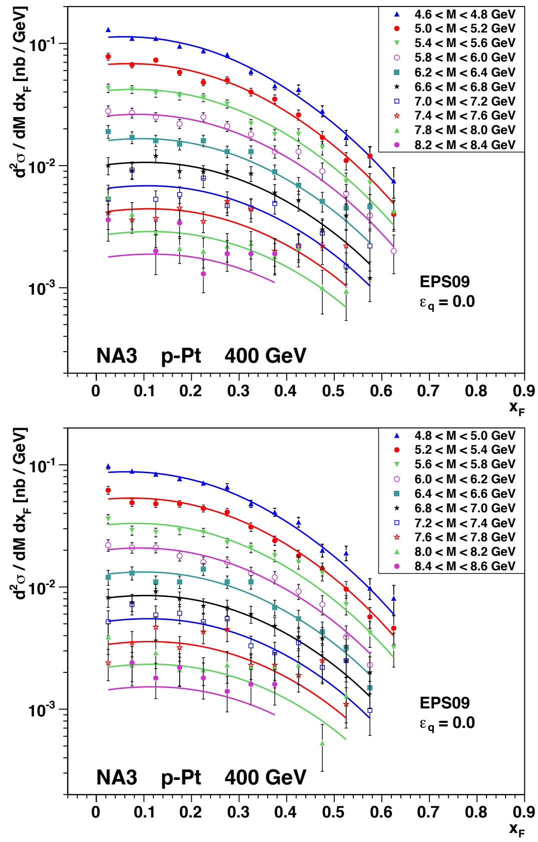

Figure 3: Drell–Yan production cross section vs. dimuon x_{F} and mass, as measured by the NA3 experiment in p-Pt collisions at 400 GeV and as calculated at NLO, using EPS09 PDFs.

NA3 measured the Drell–Yan double-differential production cross section in p-Pt collisions at E_{lab} = 400 GeV [3], in 20 dimuon mass bins, from 4.6 to 8.4 GeV/c^2, and covering the $0.0 < x_{\mathrm{F}} < 0.65$ range. Somewhat surprisingly, these accurate data points can be reproduced to a very good level with precisely the same calculation as previously done for the E866 case, apart from the change in collision energy and the inclusion of proton-neutron interactions. If we perform the calculations using parton densities modified according to the EPS09 model [4], the best fit, shown in Fig. 3, gives a K factor of 0.994 ± 0.008 (perfectly compatible with the E866 value, given the ± 12 % overall uncertainty of the NA3 data) and a very good fit quality (with a reduced χ^2 of 230 / 232). In other words, the NA3 p-Pt measurement suggests that the nuclear target has no effect on Drell–Yan production.

One might argue that the effects induced by the Pt target have been incorporated in the EPS09 model and, hence, nothing is left over that could be associated with parton energy loss. However, the NA3 data sets have not been included in the EPS09 global analysis (thereby excluding "double counting effects") and, furthermore, we obtain an equally good description of the measurements if we use free-proton PDFs ($K = 0.975 \pm 0.007$, $\chi^2/\mathrm{ndf} = 231/232$). The lack of sensitivity of the calculations to the use of parton densities modified or not by nuclear effects reflects the fact that at $E_{\mathrm{lab}} = 400$ GeV we probe an x region between the "shadowing" and "anti-shadowing" regimes, where the probability to find valence quarks or gluons is not affected by the nucleus surrounding the proton. Figure 4 illustrates this observation by showing the ratio between the p-Pt Drell–Yan production cross section calculated with EPS09 and the one calculated with free proton PDFs, as a function of x_{F} and for three mass intervals representative of the NA3 measurements.

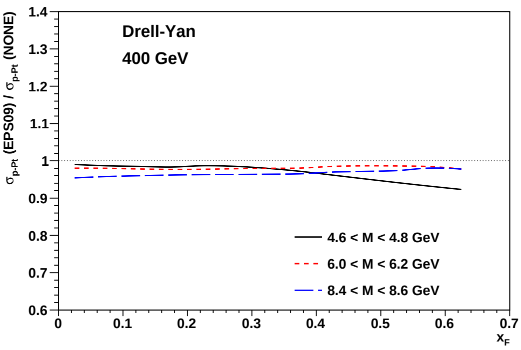

Figure 4: Effect of the EPS09 PDFs on the calculated Drell–Yan p-Pt cross section at 400 GeV, as a function of x_{F} and for three mass windows studied by NA3.

The shadowing effect is seen to be very weak and, more importantly, essentially independent of dimuon x_{F} and mass. This means that using EPS09 PDFs does not influence the shape of the double-differential cross section, simply changing its overall normalization, an effect compensated by a different K factor. This observation makes the NA3 Drell–Yan p-Pt data particularly well suited to search for nuclear effects other than those caused by changes in the parton densities.

When we calculate the double-differential p-Pt Drell–Yan cross section imposing the initial-state parton energy loss model mentioned above, for several different values of the ϵ_{q} parameter, we see that the K factor needed to describe the NA3 data increases linearly with ϵ_{q}, as shown in Fig. 5. The calculations have been made both with free proton PDFs and with EPS09 PDFs.

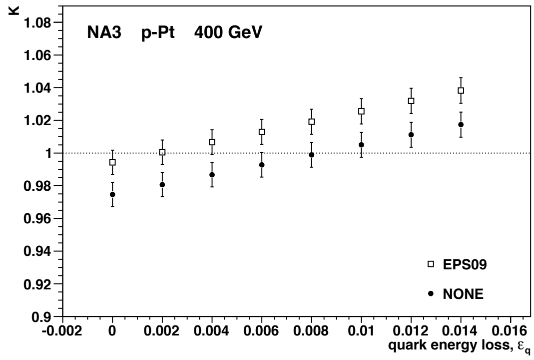

Figure 5: K factors needed to have the NLO calculations reproducing the p-Pt Drell–Yan cross sections of NA3, as a function of ϵ_{q}, when using nuclear (EPS09) or free proton PDFs.

Naturally, the K factor can only compensate for the introduction of energy loss in terms of overall normalization. Since the energy loss also induces changes in the shapes of the calculated cross sections, the quality of the fit systematically degrades as the value of ϵ_{q} increases. In this way, we can use the high-accuracy NA3 measurements to set an upper limit on the ϵ_{q} parameter, as illustrated in Fig. 6. The resulting values, calculated at 99% confidence level, are 0.0018 when using EPS09 PDFs and 0.0020 (essentially identical) when using free proton PDFs.

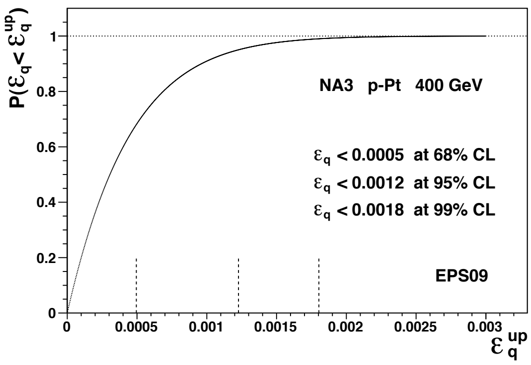

Figure 6: Illustration of the determination of the largest ϵ_{q} parameter compatible with the NA3 data.

The summary, so far, is that the high-accuracy double-differential p-Pt Drell–Yan production cross section measured by NA3 at 400 GeV is very well described by a standard NLO calculation, without including any initial-state energy loss. The only free parameter in the fit, the K factor, gets values perfectly compatible with unity, within the 12% normalization uncertainty of the NA3 measurement. These statements are valid whether we use free proton PDFs or the EPS09 PDFs. The inclusion of parton energy loss in the calculation degrades the fit quality, imposing rather strict upper limits on the amount of energy loss that can be considered while remaining compatible with the measurements. Although the numerical values mentioned above are necessarily specific to a given model, the statement that the NA3 data can be perfectly described with no energy loss at all is independent of the energy loss model we might consider.

The absence of initial-state parton energy loss effects in Drell–Yan production, according to the rather accurate NA3 data, is a very surprising result (and totally unexpected by the authors of this work). Exceptional results require exceptional evidence, or at least a second (good) look… Are there weak points in our reasoning?

The fact that we reach the same conclusion with or without employing PDFs modified by nuclear effects shows that we are not being mislead by the possibility that energy loss effects may already be included, at least in part, in the EPS09 parametrization. We could be victims of a peculiar cancellation of effects, if the NLO Drell–Yan calculation we have used contained imperfections which, once solved, would leave room for non-zero energy loss effects. However, such an explanation looks quite farfetched given that we are using a state-of-the-art calculation of a physics process generally considered very well understood and, furthermore, the same calculation gives a perfect description of the very detailed E866 pp measurements, which cover similar kinematical ranges in dimuon mass and x_F.

A major difference between the pp data of E866 and the p-Pt data of NA3 is the fact that the Pt nucleus contains neutrons. This is an important factor to keep in mind because Drell–Yan production is very sensitive to the "isospin effect", in absolute yield (proportional to the square of the quark charge) and in shape. In fact, the $\bar{u}$ and $\bar{d}$ density functions are significantly different, as clearly shown (some 15 years ago) by the NA51 [5] and E866 [6] experiments, comparing pp and pd Drell–Yan measurements. We show in Fig. 7 the ratio between the calculated p-Pt and pp Drell–Yan cross sections, as a function of dimuon x_F and for several dimuon mass ranges relevant to the NA3 measurement. We see that the isospin effect has quite a significant impact on the calculated cross sections and if we had used old PDF sets, assuming identical $\bar{u}$ and $\bar{d}$ density functions, for instance, we would surely be making a mistake which, once corrected, might leave room for a visible energy loss effect. However, our calculations have been made with the CTEQ6M set [7], and it would be somewhat surprising to conclude that this input to the calculation is affected by significant problems.

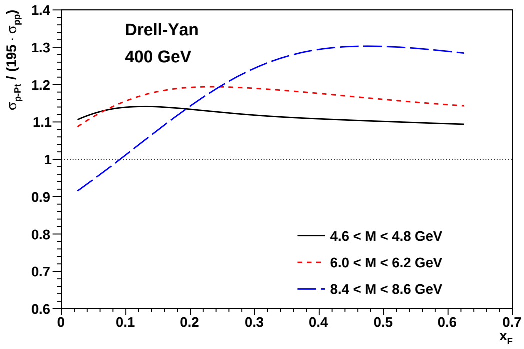

Figure 7: Ratio between the calculated Drell–Yan cross sections for p-Pt and pp collisions, at 400 GeV, as a function of dimuon x_F and for three dimuon mass windows relevant to the NA3 measurements.

Although the previous discussion gives us confidence in the robustness of our analysis, it remains important to verify that other existing measurements do not invalidate our conclusions. Naturally, it is particularly useful to study measurements where the same experiment collected data with a heavy and a light nuclear target, and published the corresponding cross section ratios. In this way, most systematic uncertainties cancel to a large extent and the nuclear effects, i.e. the relative changes from a light to a heavy nucleus, in terms of yields and kinematical shapes, can be appreciated in a more robust way. Besides, both collision systems are probed at the same energy, unlike what happens when we compare pp data at 800 GeV with p-nucleus data at 400 GeV. Finally, if the light nucleus is a deuteron or a nucleus of beryllium, or of carbon, rather than a proton, the isospin effects are strongly attenuated, an important additional advantage when we want to isolate the *nuclear* effects.

The E866 experiment measured such Drell–Yan cross section ratios, between Fe or W nuclei and Be, at 800 GeV, as a function of x_F and integrated over the mass range $4 < M < 8$ GeV/c^2 [8], as shown in Fig. 8. The E772 measurements [9], using deuterons as the light target and integrated in a slightly different mass range, are also included in this figure. The four data sets are shown as "per nucleon" cross section ratios, so that they all give values close to unity. The solid lines show the W / Be (black) and Fe / Be (red) ratios calculated using EPS09 nuclear PDFs and without including energy loss. These curves provide a very reasonable de-

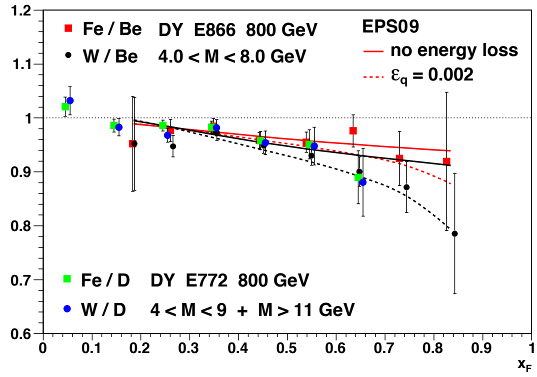

Figure 8: Drell–Yan cross section ratios as a function of x_F, as measured by E866 (Fe / Be and W / Be) and E772 (Fe / D and W / D). The curves indicate the calculated Fe / Be (red) and W / Be (black) ratios, with EPS09 PDFs, before (solid) and after (dashed) including initial-state energy loss (with $\epsilon_q = 0.002$).

scription of the measured patterns, with reduced χ^2 values of 7.9/8 (W / Be) and 1.9/8 (Fe / Be). The dashed lines represent the corresponding calculations when energy loss is included, according to the model described above and with $\epsilon_q = 0.002$. Given the rather large error bars of the data points, we cannot say that the latter calculations are better at describing the measurements; the fit quality improves for the W / Be case but degrades for the Fe / Be case and is, anyway, always "too good" (reduced χ^2 well below unity). It should be noted that these E772 and E866 measurements were included in the EPS09 analysis and, therefore, part of their nuclear behaviour should be reproduced without additional effects like the initial-state energy loss. On the other hand, the EPS09 PDFs reflect a global fit to hundreds of data sets and we cannot argue that these specific measurements play a leading role in that global analysis (especially given their rather large uncertainties).

In short, the E772 and E866 Drell–Yan cross section ratios do not show any disagreement with the conclusion we previously derived from the analysis of the NA3 data: no initial-state parton energy loss is required to explain Drell–Yan production in proton-nucleus interactions and only very small energy loss levels remain compatible with the accurate NA3 measurement ($\epsilon_q < 0.002$ at 99% C.L. in the specific model used in this paper).

We finish this paper with some comments on quarkonium production in proton-nucleus collisions, a process expected to be affected by several "cold nuclear matter" effects. One of them is, in principle, initial-state parton energy loss. However, we have just concluded that the NA3 Drell–Yan measurement sets very strict limits on the magnitude of such a mechanism. It is interesting to see how the upper limit set by NA3 for the quark energy loss compares with what would be required by existing J/ψ measurements.

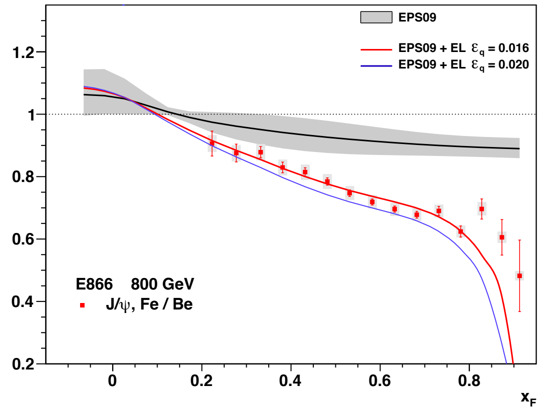

Figure 9: J/ψ production cross section ratio Fe / Be as measured by E866, at 800 GeV, as a function of x_F, compared to calculations including shadowing and energy loss.

Figure 9 shows the "per nucleon" J/ψ production cross section ratio, between p-Fe and p-Be collisions, as a function of the J/ψ x_F, as measured by E866 [11] at 800 GeV. The black line (with grey band) represents the shadowing effect (and its uncertainty) as calculated using the EPS09 model, which is clearly insufficient to describe the measured pattern. The curves complement the EPS09 shadowing with initial-state quark energy loss, calculated with the simple model exposed above and assuming that the gluon and quark energy loss parameters are related through the ratio of their Casimir factors, $\epsilon_g = 9/4 \cdot \epsilon_q$. Under these assumptions, the J/ψ pattern seems to require initial-state energy loss levels much larger than those compatible with the NA3 Drell–Yan data, indicating that some other mechanisms are responsible for the "normal nuclear absorption" of J/ψ production in proton-nucleus collisions.

In summary, we have shown that the NA3 measurements of the double-differential Drell–Yan production cross section, in p-Pt collisions at 400 GeV, provide very strict limits on the level of initial-state quark energy loss. Complementary studies, including other existing measurements and other parton energy loss models, should provide further results and facilitate their integration in analyses of quarkonium production in proton-nucleus collisions.

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